Nickel layers on indium arsenide

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We report here on the preparation and characterization of InAs substrates for *in situ* deposition of ferromagnetic contacts, a necessary precursor for semiconductor devices based on spin injection. InAs has been grown on InAs(111)*A* and (100) substrates by molecular-beam epitaxy and then metalized *in situ* in order to better understand the mechanisms that inhibit spin injection into a semiconductor. Initial x-ray characterization of the samples indicate the presence of nickel arsenides and indium–nickel compounds forming during deposition at temperatures above room temperature. Several temperature ranges have been investigated in order to determine the effect on nickel-arsenide formation. The presence of such compounds at the interface could greatly reduce the spin-injection efficiency and help elucidate previous unsuccessful attempts at measuring spin injection into InAs. © *2000 American Vacuum Society.* [S0734-211X(00)06804-9]

I. INTRODUCTION

The success of recent attempts to inject spin-polarized currents from a ferromagnetic metal into a semiconductor have been the subject of much debate, and has called into question the quality of the interface.[1–4] Recent theoretical considerations conclude that in the drift-diffusion regime spin-polarized current injection from a ferromagnetic metal into a semiconductor may not be possible.[5] In any case, a detailed look at the interface between the ferromagnetic metal and the semiconductor is a clear prerequisite for understanding what is happening during current injection. In this article, we look at the interface between one of the most widely used ferromagnetic metals, nickel, and InAs, which is often used for its high mobility and negative Schottky barrier when doped *n* type. Nickel was also selected because it offers the additional possibility of a lattice match to (111) and (110) InAs substrates. The matches were identified using the two-dimensional supercell technique developed by Zur.[6] The 0.7% mismatch of cubic Ni on the (111)InAs face is depicted in Fig. 1. Matches of this type have been experimentally demonstrated with CdTe on GaAs.

II. EXPERIMENTAL DETAILS

A. Preparation of samples

Samples were produced from commercially available 1 in. InAs(100) and (111) wafers, *n* type with carrier concentration approximately 1×10^{-16} cm^{-3}. Wafers were degreased in a standard acetone, isopropyl alcohol, deionized water degrease, after which they were placed in HCl for 1 min to remove the native oxide and rinsed in deionized water. After this, the wafers were blown dry and indium bonded to substrate blocks and introduced into vacuum. Unintentionally doped *n*-type InAs was then grown in a Perkin Elmer 430 molecular-beam epitaxy chamber until the reflection high-energy electron diffraction (RHEED) pattern indicated a smooth growth surface. The samples were then transferred *in situ* for x-ray photoelectron spectroscopic (XPS) analysis. Finally, the samples were transferred, again *in situ*, to an UHV metalization chamber for nickel deposition. Film thicknesses were monitored *in situ* by a Leybold–Inficon crystal growth monitor and verified *ex situ* by ellipsometry when possible. Nickel deposition was carried out at a variety of substrate temperatures from room temperature (RT) to 350 °C. The deposition rates were held between 0.5 and 0.7 Å/s.

B. Sample characterization

X-ray diffraction studies were performed on all samples to look for nickel films or reaction by-products produced at the interface. X-ray scans were performed with a low-resolution, high-throughput mode with a receiving slit width of 0.45 mm. Many samples were annealed for 3 min at 650 °C to see if the x-ray peak heights of the reaction products could be improved. Growths on the (100) face were characterized electrically to ensure that electrically insulating layers were not being produced.

III. RESULTS AND DISCUSSION

A. X-ray analysis

X-ray diffraction $\omega-2\theta$ scan results on the (100) samples A, B, and C from Table I are shown in Fig. 2. The addition

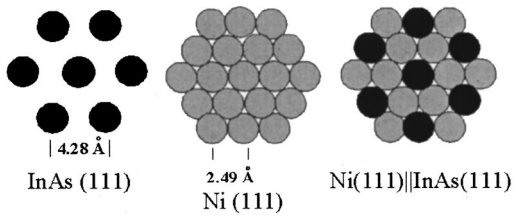

FIG. 1. Geometrical lattice match of the (111) face of nickel on (111)InAs. There is a 0.7% lattice mismatch in the plane.

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TABLE I. Summary of the samples presented.

Sample	Face	Depositon temperature (°C)	Ni thickness (nm)	Reaction products
A	100	RT	200	InNi,[a]Ni_3In[a]
B	100	150	200	InNi,[a]hex.Ni[a]
C	100	350	200	Ni_5As_2, InNi, $Ni_{11}As_8$
D	111	RT	21	...
E	111	350	1000	NiAs, Ni_5As_2, $Ni_{11}As_8$, hex.Ni

[a]After anneal.

of two extra peaks is clearly visible in the scans of sample C, deposited at a substrate temperature of 350 °C. These peaks were also visible in all other (100) samples grown at 350 °C. No evidence of reaction by-products are visible in the room-temperature growths. Samples A, B, and C were subjected to a rapid thermal annealing process in flowing argon for 2 min at 650 °C. The pre- and postnasal x-ray data are shown in Figs. 2 and 3.

Figure 4 shows the x-ray data for representative growths on the (111) face. Sample D was a 210 Å film of Ni on the (111) face of InAs. Only substrate peaks were visible in the x-ray scans both before and after annealing, as was the case with all thin (100–300 Å) Ni films on the (111) face. Sample D showed no extra peaks after annealing at 650 °C for 3 min. It is most likely that not enough Ni was deposited to form crystals detectable by x-ray analysis, or the film was amorphous. Sample E was prepared on the (111) face and taken repeatedly to 350 °C for Ni deposition and XPS analysis. After four depositions of varying thickness, the sample had roughly 1 μm of Ni on the surface, and showed many extra peaks from reaction by-products.

Few of the peaks found in the annealed x-ray data are exact matches to any of the x-ray lines for the known combinations of In, Ni, and As. Most of them are believed to be from InNi, $Ni_{11}As_8$, Ni_5As_2, $NiAs_2$, and hexagonal nickel with indium incorporated in the lattice. Table I lists the most likely impurity compounds present in each sample.

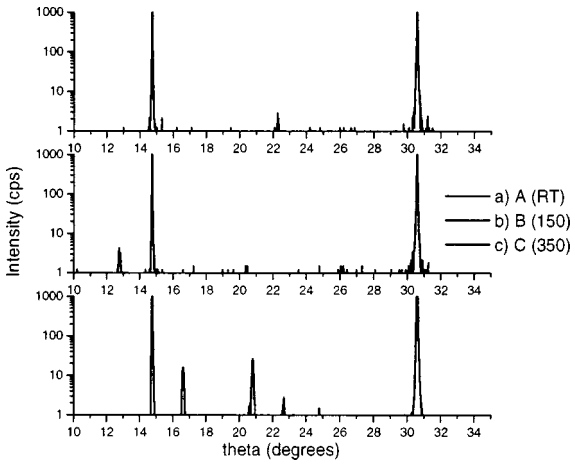

FIG. 2. X-ray diffraction scans of 200 nm Ni films on InAs(100) substrates.

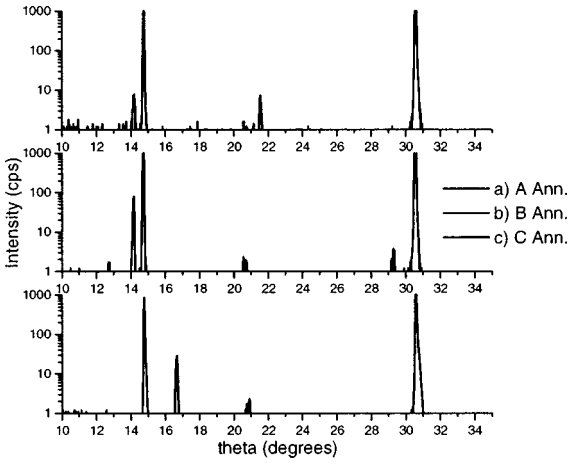

FIG. 3. X-ray diffraction scans of 200 nm Ni films on InAs(100) substrates from Fig. 2 after a rapid thermal anneal of 650 °C for 3 min.

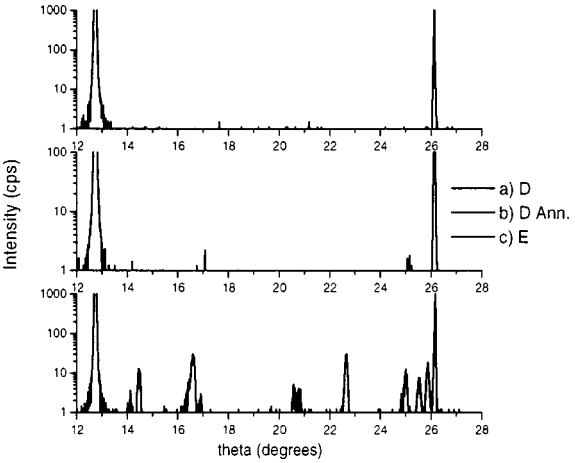

FIG. 4. X-ray diffraction scans of Ni films on InAs(111) substrates. (a) 210 Å Ni film on InAs, substrate temperature 100 °C. (b) Anneal of sample in (a). (c) 1 μm of Ni deposited at 350 °C.

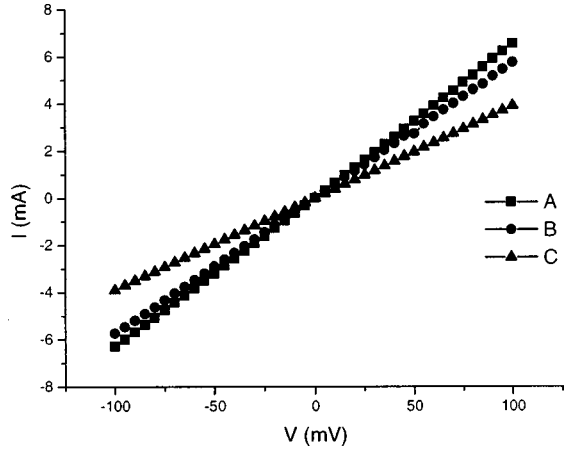

FIG. 5. Ohmic I–V curves of samples A, B, and C for 150 μm radius circular contacts.

B. Electrical characterization

To test that the contacts were indeed Ohmic, electrical measurements were carried out on samples A, B, and C. Linear I–V curves were observed for all three samples and representative curves are shown in Fig. 5. The I–V curves are from 150 μm circular pads with a 50 μm gap etched approximately 1 μm into the surface. The linear I–V curves indicate that no insulating barrier was formed during deposition.

IV. CONCLUSIONS

Ni films grown *in situ* on InAs(100) substrates yield Ohmic contacts at a wide range of substrate temperatures during deposition. No direct evidence of NiAs compounds was observed for room-temperature deposition of Ni on both (100) and (111) faces of InAs, ruling out the presence of interfacial NiAs compounds as an impediment to spin injection. Reaction by-products are only visible upon bringing the sample to higher temperatures. To date, efforts to produce epitaxial nickel on InAs(111) have been unsuccessful. Since it is apparent that low deposition temperatures are necessary to produce clean interfaces, a much lower growth rate may have to be used to offset the lower surface mobility of the deposited atoms at cooler temperatures. Most likely, the addition of an *in situ* diagnostic technique like RHEED will help to facilitate the development of a viable epitaxial growth technique, allowing one to correlate growth temperatures and deposition rates with the onset of noncrystallinity.

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